Understanding the Global Distribution of Monsoon Depressions

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LONG-TERM GOALS

This project aims to improve the understanding of cyclonic storms called monsoon depressions, which play an important role in the meteorology of the tropical and subtropical eastern hemisphere and serve as precursors for typhoons in the Indian and Western Pacific Oceans. The work undertaken here serves as part of a broader effort to better understand and predict tropical cyclogenesis and the variability of large-scale monsoon circulations.

OBJECTIVES

Synoptic low pressure systems embedded in monsoon circulations play a central role in the meteorology of the tropical Indian and western Pacific oceans during local summer, producing a large fraction of rainfall in the Indian and Australian monsoons and producing enhanced surface wind variability over oceans (Yoon and Chen, 2005; Davidson and Holland, 1987). These monsoon low pressure systems, of which the more intense occurrences are called monsoon depressions, can evolve into typhoons and are strongly correlated with dominant patterns of tropical intraseasonal variability such as the Madden-Julian oscillation (Goswami et al., 2003). Yet despite the importance of these low pressure systems, the mechanisms responsible for their formation, intensification, and propagation are not understood (e.g. Beattie and Elsberry, 2010). Furthermore, no climatology of these storms exists for regions outside of India.

This project aims to:

- document the frequency and geographic distribution of monsoon depressions in the Indian and western Pacific Oceans (both north and south of the equator),
- determine which environmental parameters (e.g. wind shear, sea surface temperature) control genesis of monsoon depressions,
- examine how the dynamical structure of monsoon depressions varies regionally and throughout the storm life cycle, and
- assess and further develop theories for storm formation and structure.

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APPROACH

This study is building understanding of the dynamics of monsoon depressions through three main tasks. In the first task, a database of the distribution of observed monsoon depressions is constructed, as only some of these storms are included in existing best-track archives of tropical cyclones. In the second task, a genesis potential index used for tropical cyclones is objectively adapted to monsoon depressions, providing a statistical description of the association of depression occurrence with environmental parameters such as wind shear and humidity. The third task will examine the dynamical structure and evolution of monsoon depressions using idealized cloud-system resolving models together with observational composites based on the climatology compiled in the first phase of the project. These dynamical studies will be strongly constrained by observations, using the statistical properties of the genesis index to verify that the idealized model systems behave in a statistically similar fashion to observations as a function of environmental parameters.

Key individuals are:

- William Boos (PI), Assistant Professor at Yale University, directs the project work flow and supervises other personnel. He is performing idealized model studies and the assessment and development of dynamical theories.
- John Hurley, postdoctoral associate at Yale University, is compiling the depression climatology and associated statistics, and will produce observational composites.
- Sarah Ditchek, undergraduate intern at Yale University, is adapting existing genesis potential indices to monsoon depressions.
- Varun Murthy, first-year doctoral student at Yale University, is performing cloud-resolving model studies of monsoon depressions in idealized domains.

WORK COMPLETED

This project began approximately 18 months before the writing of this report. In the past year, the following tasks have been completed:

1. Depression climatology: An automated feature tracking algorithm [the TRACK program by Hodges (1995)] was used to identify the locations and horizontal trajectories of cyclonic relative vorticity maxima in the ERA-Interim reanalysis. Tracks of vortices exceeding thresholds of 850 hPa relative vorticity and anomalous surface pressure were compiled for the eastern hemisphere during local summers of 1989-2010. An existing monsoon depression climatology for India (Sikka 2006) compares well with our results in the Indian domain, lending confidence to our results.

2. Genesis potential index: We developed a genesis potential index for Indian monsoon depressions, using a Poisson regression methodology (Tippett et al. 2011) with the existing climatology of Indian monsoon depressions (Sikka 2006). Once our ERA-Interim climatology is fully complete, parameters in the genesis index will be fit using that data. Our earlier efforts to use the functional form of the Emanuel and Nolan (2004) genesis index produced highly uncertain index parameters, a problem that seems to affect that methodology even for tropical cyclone datasets.

3. Dynamical studies with idealized models: We conducted preliminary integrations of the Weather Research and Forecast (WRF) model on an idealized, zonally periodic beta-plane domain with an entirely oceanic lower boundary. We also used the dry dynamical core of the global atmospheric model of the National Center for Atmospheric Research (NCAR) to simulate a mean state with a subtropical temperature maximum; this model is being used to examine the relevance of dry dynamical mechanisms of baroclinic growth.

RESULTS

Although monsoon depressions are most commonly associated with the Indian monsoon, case studies have found that storms with similar structure also occur in the southern Indian Ocean and the western Pacific. Results from our automated vortex tracking show that the number of cyclonic vortices with intensities of monsoon depressions is actually greater in those regions than in the Indian monsoon (Fig. 1). Depression-strength storms in the Indian monsoon also exhibit the shortest track lengths. Work is underway to quantify properties of these storm distributions and to produce storm composites for each region. Although the track climatology is still under development, we expect that within the next year it will serve as a valuable, publicly available database for research on monsoon depressions and tropical cyclogenesis.

The spatial distribution and seasonal cycle of genesis of Indian monsoon low pressure systems is approximately reproduced by the genesis potential index derived using a Poisson regression methodology (Figs. 2 and 3). Parameters of the fit (not shown) reveal that the genesis of Indian monsoon low pressure systems increases with vertical wind shear, a relationship that is qualitatively opposite to that seen for tropical cyclones. This lends support to hypotheses that treat these storms as products of baroclinic growth in the vertically sheared monsoon basic state. The likelihood of storm genesis was also found to increase with low-level absolute vorticity, mid-tropospheric relative humidity, and a proxy for convective available potential energy (CAPE).

IMPACT/APPLICATIONS

Results from this project are expected to have applications in weather and climate prediction:

Prediction on synoptic time scales: Studies of model skill for monsoon depression forecasting have mostly proceeded empirically, with previous authors finding sensitivity of skill to model resolution, convective physics, and initial conditions (e.g. Routray et al., 2010). Greater theoretical understanding of the mechanisms governing monsoon depressions may thus guide the improvement of forecast models. The genesis potential index developed by this study may also be useful in synoptic forecasting, providing greater understanding of the influence of large-scale parameters on depression occurrence.

Prediction on intraseasonal time scales: Intraseasonal variability in the South Asian summer monsoon strongly modulates the occurrence frequency and tracks of monsoon depressions in the Indian region (e.g. Chen and Weng, 1999). Production of a depression climatology will allow for assessment of whether similar modulation of depression behavior occurs near Australia and in the western Pacific. Knowledge of such a relationship could help forecasters use the observed phase of the MJO to improve prediction of depression formation.

Tropical cyclogenesis: Monsoon depressions serve as precursors for tropical cyclones (e.g. McBride and Keenan, 1982). An improved understanding of monsoon depression dynamics is thus expected to contribute to our theoretical understanding of tropical cyclogenesis.

Response to climate shifts: Synoptic activity and extreme rain events in the Indian summer monsoon have increased since the 1950s, but this increase is associated with enhanced activity of weaker low pressure systems and a decline in the activity of more intense systems (e.g. Ajayamohan et al., 2010). The genesis potential index developed in this project is expected to be useful in understanding how future variations in climate might influence depression activity in the broader Asia-Pacific region.

RELATED PROJECTS

Interannual variability of monsoons: We have found a statistically significant relation between interannual variations in monsoon precipitation and the equivalent potential temperature of near-surface air over land. This relationship was found to hold in all of Earth's regional monsoons, and is important because it shows that monsoon rainfall is related not only to SST, as emphasized by previous studies, but also to a thermodynamic variable that is defined over land.

Thermodynamic bias of climate model simulations of monsoons: We have shown that almost all climate models participating in the Coupled Model Intercomparison Project (CMIP) exhibit a common bias in the thermodynamic structure of the South Asian summer monsoon that is caused by poor representation of orography. The highly smoothed topography used in these models allows dry air from the deserts of western Asia to penetrate the monsoon thermal maximum, reducing model upper-tropospheric temperatures and suppressing monsoon precipitation.

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Boos, W. R. and J. V. Hurley: Thermodynamic bias in the multi-model mean boreal summer monsoon. *Journal of Climate* [in press, refereed].

Hurley, J. V. and W. R. Boos: Interannual variability of monsoon precipitation and subcloud equivalent potential temperature. *Journal of Climate* [refereed].

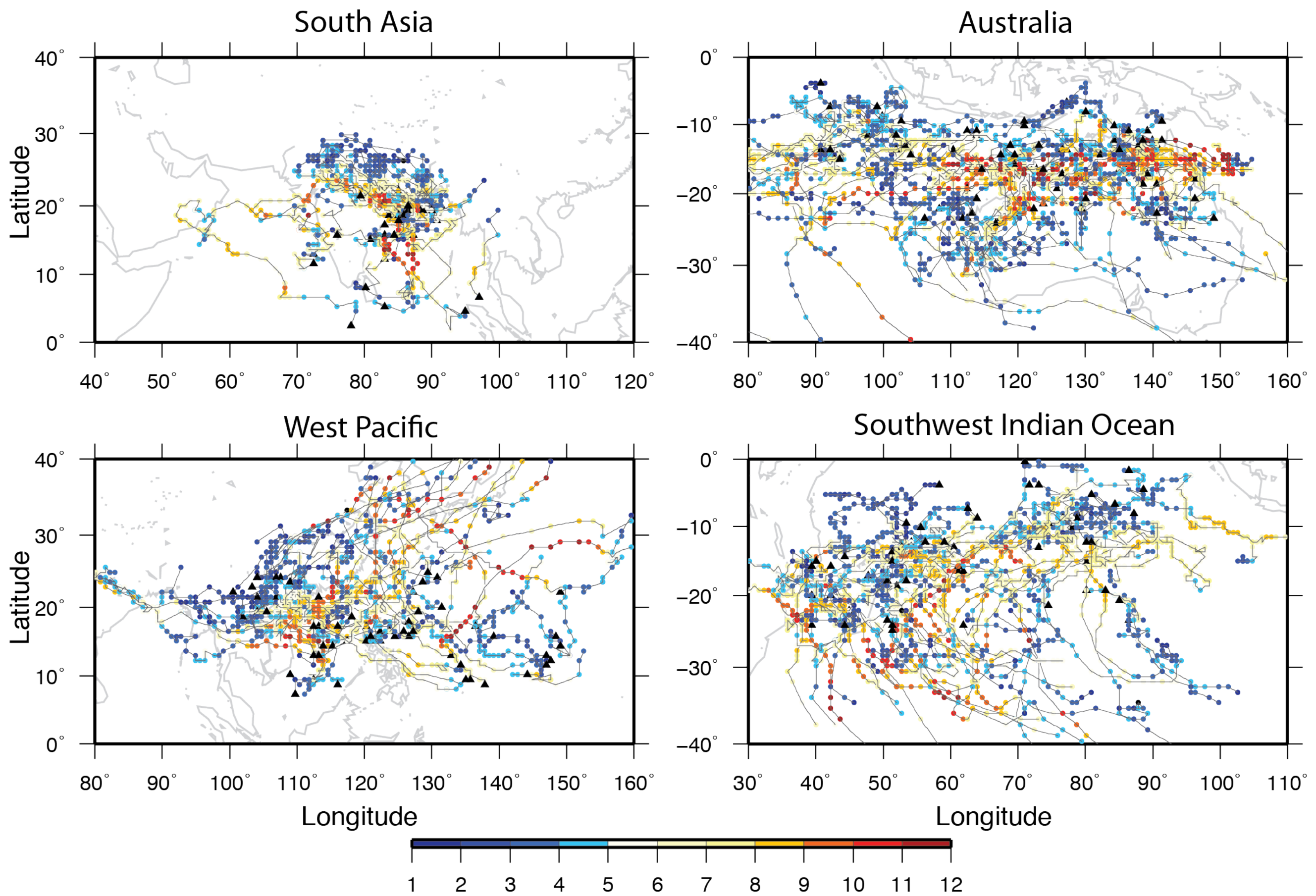

Fig. 1: Tracks of cyclonic vortices with intensity of monsoon depressions 1989-2003 during local summers (May-Sept. for northern hemisphere and Nov.-March for southern hemisphere). Black triangles denote genesis locations, and colored dots represent the 6-hourly 850 hPa relative vorticity, in units of 10^{-5} s^{-1}.

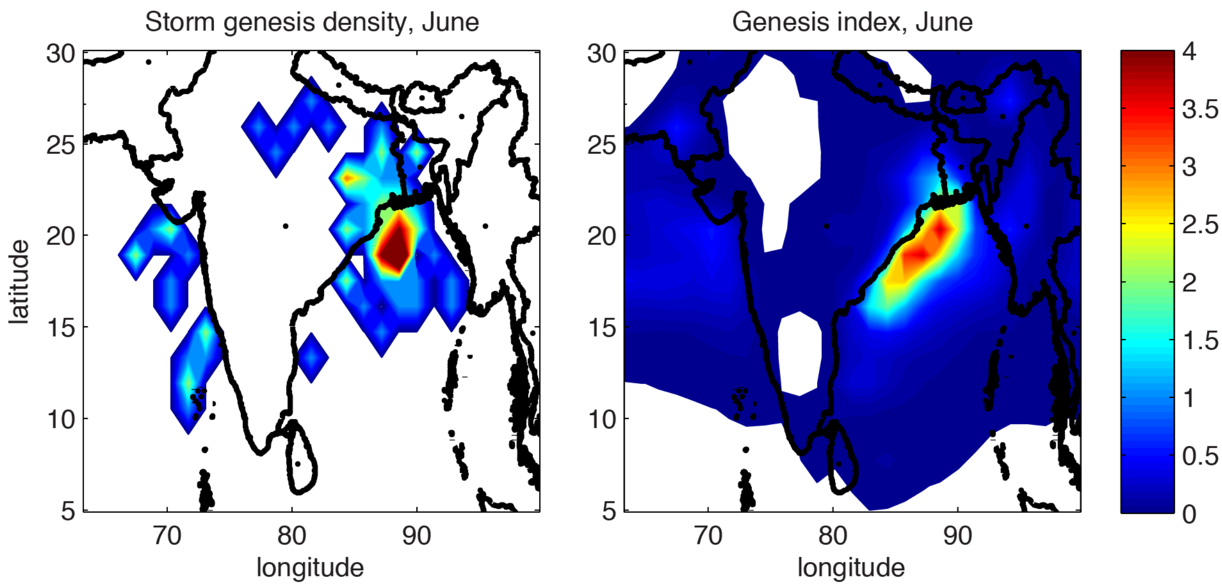

Fig. 2: Comparison of observed genesis density (left) and that predicted by our genesis potential index (right) for all low pressure systems in the Sikka (2006) climatology, for 1979-2001 in June. Colors in left panel are displayed only in locations of observed storm genesis, and units are number of storms over the period of the record.

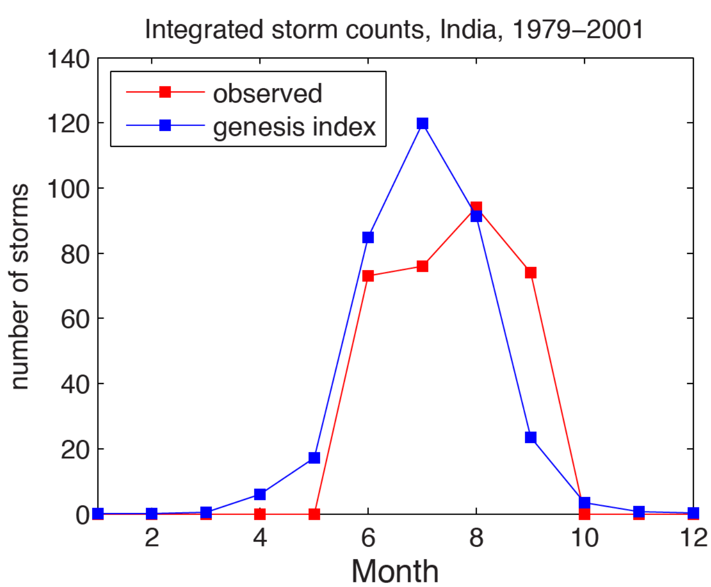

Fig. 3: Seasonal cycle of storm counts horizontally integrated over the Indian monsoon domain for the Sikka (2006) climatology (red line) and that predicted by our genesis index (blue line) for 1979-2001. Vertical axis shows number of storms over the period of the record. The Sikka (2006) climatology has data only for June-Sept., so its counts are set to zero outside those months.